Research paper
Quantifying aperture, spacing and fracture intensity in a carbonate reservoir analogue: Crato Formation, NE Brazil


A R T I C L E   I N F O
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A B S T R A C T
The characterization of fracture networks in carbonate reservoirs represents a primary approach to understand the processes of fluid flow. The study of outcrop analogues has been used to enhance the understanding of the relative contribution of fracture networks to reservoir permeability. The outcrop data can overcome scale limitations and/or lack of consistency of subsurface datasets (e.g. seismic, well logs, and cores). This paper presents the fracture characterization of the Aptian-Albian lacustrine laminites of Crato Formation (Araripe Basin, NE Brazil), which have been investigated as an analogue to some of the observed carbonate facies present in the pre-salt reservoir sequence of the Brazilian marginal basins. In order to provide fracture attributes for Discrete Fracture Network (DFN) modelling we investigate spacing and aperture distribution, length and intensity of fractures based on the use of traditional scanline (macro and microscale) method. The main fractures identified in the Crato Formation are shear and extensional fractures and with stylolites also present. In this study, we focused on vertical veins, which strike in two principal directions, NNW-SSE (Set 1), NE-SW (Set 2), and are filled or partially filled by calcite or gypsum. The relationship between length and aperture of vertical veins is linear. Apertures and spacings of fractures in both sets 1 and 2 follow power law and lognormal cumulative frequency distribution functions, respectively. Fractures of Set 2 are more likely to be clustered than are fractures of Set 1, which have a wider kinematic aperture. This structural database can be used to populate computational models that consider the widespread fracture system in the fluid flow simulation of carbonate reservoirs.

1. Introduction
Fracture characterization has motivated an increasing number of investigations regarding reservoir numerical modelling due to its impact on fluid flow prediction of ground water and hydrocarbon reservoirs (Guerriero et al., 2013; Massaro et al., 2018; Laubach et al., 2018a). Fracture network permeability is governed by the occurrence of fractures, their aperture, spacing, length, topology, and whether or not they are filled with cement (National Research Council, 1996). However, a large portion of fractures are below the limit of seismic resolution and these fractures are under sampled due to the limited area investigated by subsurface probes and the consequent small size of subsurface datasets (Bonnet et al., 2001). One way to correct for this lack of information regarding sub seismic fractures is the study of outcrop reservoir analogues (Bisdom et al., 2017). Outcrop studies make it possible to construct realistic 3D models (geological and numerical) using data accessible at the Earth’s surface, which cannot otherwise be observed in cores or seismic surveys (Hardebol and Bertotti, 2013; Watkins et al., 2015; Healy et al., 2017).

Analogue reservoir modelling using outcrop datasets can be applied to numerical simulations using equivalent fine scale and upscaling to relevant properties (e.g. porosity and permeability) taking into account the resultant structural geometries from DFN models (Falcão et al., 2018).

This study focuses on fracture characterization of a carbonate reservoir analogue from the laminites of the Crato Formation, Lower
Cretaceous lacustrine section of the Araripe Basin (AB), NE Brazil (Fig. 1). The laminites of the Crato Formation are analogous (stratigraphic equivalent) to one of the carbonate facies encountered in the pre-salt reservoir of the Brazilian marginal basins (Catto et al., 2016; Terra et al., 2010).

We collected data that provide parameters for the multi-scale integration (thin sections, outcrops) of reservoir models, supplying structural data for improved representation of geological heterogeneities, especially extensional fractures. To develop a fracture system database that can be used in subsequent reservoir analogue modelling, we applied the scanline technique to the laminites, focusing on the following fracture attributes: orientation, crosscutting relationships, composition, texture of fracture fill, fracture aperture-size and spacing (Gomez and Laubach, 2006; Gale et al., 2007; Guerriero et al., 2010; Hooker et al., 2009; Marrett, 1996; Ortega et al., 2006; Priest, 1993; Sanderson and Nixon, 2015). We also quantified fracture intensity with the Normalized Correlation Count (NCC) computer program (CorrCount), which provides a spatial arrangement by normalizing to expected values for randomly arranged fractures (Marrett et al., 2018). The NCC describes fracture positions in space, indicating the occurrence of fracture clusters, which is a crucial element needed to support DFN models and numerical simulations.

Our study develops a conceptual structural evolution model of fractures in the Crato Formation’s laminites. Furthermore, this research is the first to undertake quantification of the aperture, spacing and fracture intensity of vertical veins from a Brazilian pre-salt reservoir analogue. This data will allow us to better parametrize future numerical simulations of carbonate reservoir analogues.

2. Geological settings

The study area is located in the AB, the largest interior basin of Northeast Brazil. The Crato Formation belongs to the post-rift tectonostratigraphic sequence and represents the main lacustrine phase of the AB (Assine, 2007; Neumann, 1999) (Fig. 1b). The AB North Rim is mostly well known for its pterosaur bone beds and the Crato Formation represents a famous lagerstatte deposit that preserves pristine soft body fossils (Barling et al., 2015; Field and Martill, 2017). The origin of the laminites is still a matter of debate, with some arguing for an inorganic authigenic origin and others that point to a for microbial influence as the main source (Heimhofer et al., 2010 and Catto et al., 2016, respectively). Our study was carried out at the best-expressed level, which is exposed in 3 Irmãos complex quarry, northern region of the basin, Nova Olinda, Ceará state (Fig. 1). The 3 Irmãos quarry contains tridimensional exposures providing a valuable opportunity to collect information on the contribution of fracture networks.

This study takes the laminites of the Crato Formation as a potential analogue of low permeability carbonate facies of pre-salt reservoirs of Barra Velha Formation, Santos Basin (Fig. 2). This is mainly due to their correspondence in depositional age, and similarities in lithology, petrophysical and geomechanical properties (Terra et al., 2010; Miranda et al., 2016; Catto et al., 2016; Menezes et al., 2016; Zihms et al., 2017).
data has great value, 1D scanline data is most readily compared to subsurface observations. Although our quantitative data is 1D, we also describe the 2D topology of the fracture patterns.

The following features were recorded through the linear scanline (1-D) readings: (1) the spacing (perpendicular distance) between fractures in the same set, (2) the kinematic aperture, (3) the fracture orientation, (4) the morphology, (5) the crosscutting relationships between fractures and (6) the composition of the fracture fill (Fig. 3a). To measure the fracture apertures in the macroscanline, we used a fracture-width comparator with a collection of apertures measuring 0.05–5 mm (Fig. 3b) (Ortega et al., 2006). The comparator shows logarithmically graduated lines such that differ by approximately constant increments when plotted on a logarithmic axis. In order to have greater scale range in surveys the total lengths of the scanlines made along pavements and thin sections were normalized and compared for each set of extension fractures. In this paper, the microscanlines were performed according to the methods in Gomez and Laubach (2006). We selected vertical veins that show no field evidence of shear displacement, subsequent deformation, any of which might indicate alteration of the original aperture (Vermilye and Scholz, 1995).

We also investigated the distribution of aperture and spacing of opening-mode fractures by comparing goodness-of-fit for power law, exponential or lognormal distributions using the log-log plots of aperture (b) and fracture spacing (s) versus cumulative frequency (F) (Hooker et al., 2014). Following Santos et al. (2015) we established 95% confidence intervals for each of the best fit distribution to eliminate sampling biases in fracture data acquisition (scanline). These biases are recognized as censoring and truncation artifacts, caused by geometrical restrictions and the sampling dimensions (Pickering et al., 1995; Ortega et al., 2006). Censoring artifacts are common because large structures may be undersampled due to the limited length of scanlines across the outcrop. Since the outcrop surveying procedures include naked eye and hand lens observations, truncation normally occurs owing to the difficulty of measurement of small aperture fractures (0.05 mm). In this study we performed microscanlines to resolve fracture apertures down to the micron scale using high resolution imaging methods (Milliken and Laubach, 2000; Hooker et al., 2014). Following eliminating artifacts due to censoring and truncation we selected a representative series to have a better distribution fit and with fewer errors and uncertainties.

Using the CorrCount, NCC computer program the spatial arrangement of bed-normal fractures was preliminary quantified (Marrett et al., 2018). The NCC method provides a quantitative analysis of the degree to which fracture sets are clustered and can distinguish between even spacing (periodic or anticlustered), clusters arising due to random arrangement, and clustering that is stronger than a random signal (Marrett et al., 2018; Laubach et al., 2018b; Li et al., 2018). The CorrCount provides analytical and Monte Carlo solutions for randomized input spacings and allows a 95% confidence interval to be constructed for randomized sequences. If fracture intensity falls either above or below the upper or lower confidence limits, the corresponding fracture spacing is statistically significant (Marrett et al., 2018; Laubach et al., 2018b). In this work the NCC settings for both fracture sets were: a) uncertainty estimates = Monte Carlo; b) linear windowing = 0; and c) normalized. Furthermore, the NCC quantifies the coefficient of variation (CV) of the population of inter-fracture spacings, $CV = \sigma/\mu$, where $\sigma$ is the standard deviation of the population of spacings and $\mu$ is the arithmetic mean. For randomly arranged fractures CV is near 1; $CV > 1$ if fractures are more clustered than random; and $CV < 1$ for those fractures having less clustering than random and it indicates anti-clustering (Gillespie et al., 2001; Hooker et al., 2013; Marrett et al., 2018).
4. Results

4.1. Structural characterization

Fractures identified in the laminites of Crato Formation were principally shear and extensional fractures. We also found stylolites, horizontal veins and vuggy fractures. The shear fracture planes were identified in conjugate pairs with a preferential N5E direction and moderate dip (between 20 and 75°) towards ESE and WNW (Fig. 4d, e-f). These structures usually occur in association with drag folds formed...
in the enclosing rock. These evidences suggest that during the generation of these fractures, the laminate deposits had both semi-consolidated and unconsolidated parts. This fact explains the variation of fracture angles (20°–75°), considering that some fractures were developed when the rock was consolidated (brittle regime) and other when the rock was more plastic (ductile regime). The angular variation between the planes of the conjugate pairs of shear fractures depends also on the confining pressure (extent of deformation), the temperature and the pore fluid. Thus, the shear fractures of laminates can be interpreted as syn-sedimentary structures generated during the diogenetic phase. Furthermore, due to mechanism deformation observed in macroscopic and microscopic samples, such as granular flow and sliding and its truncation by younger structures, the observed shear fractures are classified as the earliest structures being formed in the laminates. Vertical stylolites were identified normal to the bedding striking preferentially N50-60E (Fig. 4g, h-i). The horizontal veins are parallel to bedding, which dips uniformly at 2°–6° to the ESE (Fig. 4a-b-c).

The vuggy fractures we identified are directly related to the karst features observed in the laminates of Crato Formation. These features principally strike N60E, N90E and N30W, and are associated with joints, shear fractures and horizontal veins (bedding), possibly through the epigenetic processes of dissolution. The fact that the dissolution occurred along a disperse group of pre-existing structures explains the aleatory observed in their rose diagram (Fig. 5). The vuggy fractures are a result of the intense dissolution process in some outcrops, with the potential to reach the scale of small caverns (Fig. 5).

4.1.1. Extensional fractures

The extensional fractures were classified as vertical joints and veins. The joints occur without macroscopically visible fill or are partially filled with calcite and/or gypsum (Fig. 6). In some outcrops dissolution features are visible and filling of calcite and/or gypsum occur on the walls of the joints, indicating that these processes can be related to the telodiagenetic processes, by the effect of infiltration of meteoric water due to the exhumation of the deposits and subsequent erosion of the strata. The observed veins are totally filled with calcite and fill textures can be classified as syntaxial (Fig. 6). Furthermore, these structures essentially indicate that the calcite fill was precipitated in the subsurface as the fractures evolved (Urai et al., 1991; Ukar and Laubach, 2016).

Vertical extensional fractures strike in two main directions: a) Set 1 - NNW-SSE (mean vector 335 Az); b) Set 2 - NE-SW (mean vector 48 Az) (Fig. 6a-b). These fracture sets were defined in the field by their orientation. And based on crosscutting relationship, both Set 1 and Set 2 are contemporaneous in age of deformation.

The vertical vein networks of Crato Formation laminates have three types of intersections: 1) I-node; 2) Y-node, which has three branches; 3) X-node that has four branches (Fig. 7) (Sanderson and Nixon, 2015). Although all three nodal types were present, the interaction between X and I-nodes branch structures was the most frequently observed.

4.2. Fracture aperture, spacing and length

In this study, shear-mode fractures, horizontal veins and stylolites were not included in the scanline surveys due to the difficulty of measuring the exact displacement of the faults, and because the stylolites were undersampled in many of the scanlines due to their orientation and due to the low abundance in the study area. Our statistical study focused only on vertical extensional fractures (veins).

We measured 75 kinematic apertures of Set 1 vertical veins along four scanlines measured on the outcrop, totaling approximately 90 m long with a strike of N65E. The microscanline of Fracture Set 1 intersected 20 microfractures. The macro and micro scanline data processing allowed us to describe the aperture-size distribution in the log-log plot of Fig. 8 (cumulative frequency versus kinematic aperture) where apertures range from 0.004 to 30 mm. Set 2 extensional fractures were measured in four macrocanlines, totalling 59 m long, striking at N38W. The scanlines intersect 173 fractures with apertures ranging from 0.05 to 66 mm. We measured only three microfractures in the microscanlines of Fracture Set 2 where apertures range from 0.01 to 0.005.

Both fracture sets aperture distributions are best described and represented by a power-law rather than lognormal or exponential distributions (Fig. 8a, d). The observed power law in a fracture distribution log-log graph (sets 1 and 2) shows that the data form a drop-off at the large-size limit of the distribution (i.e., the part of the distribution representing macrofractures, indicating a deviation from the power-law scaling trend) (Fig. 8b, e). This deviation may be either real or the effect of sampling biases, such as censoring artifacts (Ortega et al., 2006; Hooker et al., 2013). In the part of the distribution representing small fracture apertures (b < 0.05 mm), it is also possible to observe the effect of truncation artifacts (Ortega et al., 2006). The power laws of sets one and two indicate a 95% confidence interval. Consequently, the fracture aperture values, which fall within this confidence interval, represent the most reliable data set (effective series - best fit function). Otherwise, the outliers should be interpreted as the data related to sampling biases. Thus, the censoring biases were represented by large fractures with b > 3 mm (Set 1), b > 60 mm (Set 2) and the truncation biases were represented by values of b < 0.01 mm for both sets (Fig. 8b,e).

The cumulative frequency (effective series) of fracture sets 1 and 2 follow a power-law aperture-size having a scaling exponent of about -0.44 and -0.66, respectively (Fig. 8c). After eliminating the artifacts (censoring and truncation) we identified that there is a consistent improvement in the R² (coefficient of determination) values from 0.93 to 0.97 in Set 1 and 0.97–0.99 in Set 2.

The cumulative frequency of fracture spacings (s) of sets 1 and 2 follow a lognormal distribution better than power law or exponential fits (Fig. 9a, d). Considering the 95% confidence interval of the log-normal regression, it was possible to remove the outliers interpreted as artifacts of fracture spacings (Fig. 9b, e). This process allowed us to have an effective series with a greater determination coefficient (R²), where truncation biases were represented by values of s < 1 mm (Set 1), s < 2 mm (Set 2) and censoring biases were represented by large spacing values of s > 7000 mm and s > 2000 m, of sets 1 and 2, respectively (Fig. 9c, f).

Fig. 10 shows the linear adjustments of the fracture sizes 1 (m) as a function of the apertures ‘b (mm)’ for sets 1 and 2. In this case, the general equation of a line can be defined as follows:

\[ Y = A \times X + B \]  

Where Y is the dependent variable and X is the independent variable. ‘A’ is called the angular coefficient and ‘B’ is the linear coefficient. The angular coefficient refers to the slope of the line adjusted from the least squares method. In this work, we have the independent variable aperture according to the dependent variable length. After the adjustment with the least squares method, we obtain the equations of the lines shown in Fig. 10. Therefore, if two straight lines have the same angular coefficient, it means that the rate of change, i.e. the first derivative, of one variable (aperture) relative to another (length) is equal.

Between the two sets of fractures, we noticed that there is practically the same angular coefficient (b₁ = 0.95 and b₂ = 0.91) for both adjustments. This means that the ratio of fracture size to aperture size has the same rate of change. Accordingly, the variation behavior of the aperture as a function of length is practically the same. Fractures of Set 1 have an average of length and aperture values of 1.15 m and 0.5 mm, respectively. A mean value of 0.32 m (length) and 0.095 mm (aperture) was recorded for Set 2.

4.3. Fracture intensity

Here we present the fracture spatial arrangement based on NCC aimed at assessing whether the vertical vein datasets can be quantified
and distinguished from random clustering (Marrett et al., 2018).
Fracture Set 1 has a CV value of 1.76, indicating a more clustered than random spacing. Fracture Set 2 has a CV value of 2.16. Note that CV values for Set 1 are lower than those from Set 2, which could indicate that Set 2 fractures are more clustered, or irregularly spaced. The average fracture intensity (number of fractures across scanline length) values of sets 1 and 2 are 1.01 and 2.98, respectively (Table 1).

Fig. 11 shows the normalized fracture intensity plot with the horizontal axis representing the distance in meters along the scanlines performed on the outcrop pavement across fractures sets 1 and 2, respectively. The vertical axis shows fracture intensity. The calculated intensity values are normalized by expected intensity for randomly spaced fractures (Marrett et al., 2018).

The normalized fracture intensity of Set 1 shows five peaks above the upper 95% confidence limit: a) 41–42 m; b) 43–47 m; c) 48–50 m; d) 60–66 m and e) 84.5–90 m, with distances between clusters of 1 m, 1 m, 10 m and 18.5 m, respectively (Fig. 11). This suggests that these intervals have statistically significant values and deviate from random. Fractures Set 2 shows six intervals with statistically positive anomalies: a) 10–11 m; b) 13–15 m; c) 44–46 m; d) 46.5–49 m; e) 49.5–50 m and f) 58 m (Fig. 11a). Distances between clusters of fracture Set 2 are 1 m, 2 m, 29 m, 0.5 m, 0.5 m and 8 m. Fractures of Set 2 have less distance between clusters comparing to fractures of Set 1. These results agree with a CV of 1.76 and 2.16, set 1 and 2 (most clustered), respectively (Table 1).

5. Discussion

5.1. Chronological relationship between fractures

The chronologic relationship between the structures of the laminites of Crato Formation, are mainly based on their crosscut relationship and can be summarized, from oldest to youngest by: 1) shear fractures; 2) vertical stylolites; 3) vertical veins; 4) bed-parallel veins and 5) joints and vuggy fractures (Fig. 12).

It is possible to infer that the first deformational cause that impacted the laminated carbonates was a horizontal extension in a WNW - ESE direction. This regime generated the conjugate pairs of shear fractures (normal faults), typical of an extensional environment. These are characterized by syn-sedimentary deformation based on granular flow deformation mechanism developed in an early and pre-consolidated phase when sediments porous where full of fluid. Conforming to the extensional environment model, within which the Crato Formation is positioned, represented by the post rift interval of the AB, it would be
normal to encounter depositional stylolites in the horizontal position, concordant with the characteristic of the shear and extension fractures of the formation. Instead, we observe vertical stylolites. One hypothesis for the occurrence of these structures with vertical planes, perpendicular to bedding, is the action of a local field of horizontal shortening. This local horizontal compression could have been generated by displacement of the conjugate shear fracture pairs, described above. The shear fractures and vertical stylolites are cut by extensional fractures (joints and veins), indicating that the shear fractures were formed in an earlier deformation event.

According to the classification of fractures proposed by Nelson (2001), the opening-mode fractures mapped in the laminites can be classified as regional extension fractures. Some aspects of the regional geologic context of the AB strongly control the orientation of these fractures. These extensional fractures in the laminites occur parallel to the preferential direction of the structural alignments observed on a regional scale in the AB (NW-SE and NE-SW) (Miranda, 2015).

Considering that the veins and joints present a difference in the type and nature of filling, it is possible to hypothesize that the veins are older and occurred under burial conditions (subsurface) when compared with joints. The formation of the laminites's vertical veins may be is associated with the late stages of the AB's burial. Followed by the uplift phase of AB during the Cenozoic (Gurgel et al. 2013), the joints possibly were originated from the veins, by erosion of the overlying formations due to the process of uplift-related thermoelastic contraction or exposure. This process would explain the occurrence of joints with a significant aperture enlargement due to aerial exposure. Locally, these structures also were partially filled with gypsum-rich material, possibly derived from the Ipubi Formation. Due to the effect of continuum exhumation process, also pressure release fractures were formed sub-horizontal and parallel to bedding.

Finally, due to the dissolution of shear fractures, extensional fractures and mostly release joints planes; vuggy fractures were generated. These structures were formed due to the uplift of the Crato Formation and evolved preferentially along preexisting planes of weakness (shear, extensional and bedding parallel fractures), generating karstic features in the laminites.

5.2. Implications for numerical modelling

Discrete fracture network models (DFN) are critical to the development of effective reservoir models (e.g. Dershowitz and Einstein, 1988; Cacas et al., 1990), especially in frequently difficult to access ultra-deep petroleum plays. Our data suggest a multiplicity of specific factors generated the observed fracture distributions in the laminites pre-salt analogues from the Crato Formation, NE Brazil. Although differences between our study area and the corresponding subsurface analogue due to regional tectonic history and local diagenetic conditions are likely to exist, useful up-scalable parameters can nevertheless be extrapolated from the results acquired surveying the chosen exposed reservoir analogue.

Instead of trying to investigate 2-D or 3-D fracture patterns, we carried out a robust 1-D multiscale approach (macro and microscanslines) to quantify opening-mode fracture attributes more accurately. We found that kinematic aperture data can be fit using representative power-law and log-normal distribution. Likewise, we documented patterns of normalized fracture intensity and the relationship between kinematic aperture and fracture length. Our field data allow us to derive an accurate representation of the power-law fracture aperture distribution (fracture sets 1 and 2) over a wide size range, since data was obtained from two data collection scales (micro and macroscale), as shown in Fig. 8. The spacing frequency of fracture sets 1 and 2 indicate that the fracture population fits a log-normal distribution (Fig. 9). The log-normality of the distribution implies that...
the average spacing values is less than the standard deviation, indicating that the fractures are clustered around low spacing values (CV > 1) (Gillespie et al., 2001; Marrett et al., 2018). This is congruent with a CV of 1.76 and 2.16, set 1 and 2, respectively (Table 1).

The relationship between fracture aperture versus length implies that all fractures from sets 1 and 2 have the same angular coefficients. This might suggest the same driving stress at the time of fracture filling (Olson, 2003). These data are consistent with crosscutting relations.

Fig. 8. Log-log plots of cumulative frequency versus fracture aperture showing the trendlines corresponding to the best fit of the scanline data to power law, lognormal and exponential equations for fracture sets 1 (a) and 2 (d). The scanline correlation with the complete data sets 1 (b) and 2 (e). The effective series (Set 1 - c and Set 2 - f) after the exclusion of data interpreted as artifacts (truncation and censoring bias). Circles = truncation and censoring artifacts.
observed in the field, which suggest that sets 1 and 2 have a contemporaneous deformation timing.

The applied NCC computer program (CorrCount) (Marrett et al., 2018) rigorously quantifies what constitutes a cluster in the normalized fracture intensity. This approach was used along 1D scanlines to compare fracture intensity for different fracture sets. Our results demonstrate that fracture Set 2 is more clustered than Set 1. Possibly, the dominant influence over fracture intensity or spacing, highlighting the potential importance of diagenetic and mechanical-property history (Ortega et al., 2003) is controlled by regional weakness of basement rocks that underlying the Crato Formation (Miranda, 2015).

These results can be used to understand the impact of fracture aperture and clustering on permeability, and their implications for subsurface reservoirs. Furthermore, fracture clusters have been identified as widespread features in reservoir rocks and need to be included in reservoir models (Laubach et al., 1995; Questiaux et al., 2010; Belgrano et al., 2016; Li et al., 2018).

Massaro et al. (2018) performed DFN modelling based on a

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**Fig. 9.** Log-log plots of cumulative frequency versus fracture spacing showing (a–c) the trendlines corresponding to the best fit of the scanline data to power law, lognormal, and exponential equations, in which the lognormal provides the best fit for the data; (b–d) the scanline correlation with the complete data set for both sets, and (c–f) the effective series after the exclusion of data interpreted as artifacts (truncation and censoring bias). Circles = truncation and censoring artifacts.
multiscale approach considering mesoscale (outcrop) and large scale (aerial photos), analyzing a fractured carbonate succession located in the Sorrento Peninsula, an analogue of buried reservoir units of southern Italy’s major oil fields. In these analyses the authors carried out 1-D scanlines and observed that the final model provided useful insights related to fluid flow response in carbonate reservoirs. Blessent et al. (2009) applied a finite element simulation comparing the DFN models and equivalent models for a contaminant transport in fractured media based on field-scale fractured aquitard overlying an aquifer.

The tectonic history behind the fracture distribution and intensity of the Crato Formation laminites provides a useful basis upon which to plan and process data obtained from Brazilian Pre-Salt carbonates, contributing to building a workflow of a robust conceptual DFN modeling. Beyond the importance of obtaining fractures attributes to help parameterize DFN models, our data provide a regional background deformation, which in most of the cases is neglected in the models, where users generally associate high-intensity fracture values with large-scale structures. At the stage of this study, NCC results show that fracture related structure, in Crato Formation, is clustered and related overall to a regional stress field and possibly with the mechanical stratigraphical thickness at the moment of deformation then to the seismic scale structure. However, this deserves more and more investigations, with combining of subsurface data such as seismic, gravimetric and magnetometric data. In addition, this could corroborate the indicative of background fractures tend to occur in clusters in the subsurface, with larger spacing and smaller aperture as it gets deeper based on geothermal data in Iceland (Gudmundsson, 2011). Likewise, the clusters spacing measurements can be used to populate the DFN model reducing some uncertainties related to fractures distribution in the stochastic simulation, where the fractures can be assumed randomly located and with homogeneous spatial distribution. Also, it can influence the strategies of well installing, especially in cases in which are applied hydraulic fracturing procedures where the control of interaction between hydraulic induced and natural fractures is very important.

In summary, this research shows that their role is evidently critical to understanding and enhancing the DFN models and fluid flow simulations of naturally fractured carbonate reservoirs.

6. Conclusions

The principal structures identified in the laminated carbonates of Crato Formation are shear and extensional fractures (joints and veins). Secondary structures include horizontal veins, stylolites and vuggy fractures. Most of the extensional fractures documented in outcrops are classified as vertical veins filled by calcite or gypsum. We describe two

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<th>Table 1</th>
<th>Scanline descriptions. b = aperture; CV = coefficient of variation.</th>
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<td>Fracture set</td>
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main populations of extensional fractures: a) Set 1, NW–SE; Set 2, NE–SW. The fractures of sets 1 and 2 have a cumulative frequency of aperture and spacing follow a power law and log-normal distribution, respectively. Using CorrCount analysis of fracture intensities it was possible to identify that fractures of Set 1 have a higher intensity and are less likely to be clustered than are fractures of Set 2, which have a wider kinematic aperture. Our results show that these methods (macro and microscale) integrated in the suggested workflow, are an important tool for collecting fracture attributes, which can be used to model a more reliable DFN, providing important equivalent properties, after upscaling it, for upcoming fluid flow simulations of carbonate reservoirs.

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References


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Fig. 12. Block diagram showing conceptual model of structural features of the laminites of Crato Formation. Sh - shear fracture; St - stylolite; Vv - vertical vein; J - joint; Hv - horizontal vein; Vg - vuggy fracture.


